DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

NBS TECHNICAL NOTE 996

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Mechanical Properties of Adobe

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Mechanical Properties of Adobe

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Issued May 1979

National Bureau of Standards Technical Note 996
Nat. Bur. Stand. (U.S.), Tech. Note 996, 45 pages (May 1979)
CODEN: NBTNAE

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1979

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
Stock No. 003-003-02066-4 Price $2.25
(Add 25 percent additional for other than U.S. mailing)

☆ U.S. GOVERNMENT PRINTING OFFICE : 1979 O—281-067 (126)

ABSTRACT

Relationships between the compressive strength and creep, and the moisture contents of adobe were investigated. Moisture was found to have a deleterious effect on these mechanical properties of adobe, its severity increasing with increasingly higher relative humidities and higher moisture contents. It was concluded that rain and gound water would have a greater deleterious effect on the mechanical properties of adobe than high relative humidities.

The physicochemical properties of adobe, mix proportions, drying conditions, and shrinkage of specimens were also found to influence the compressive strength of adobe. Procedures for preparing, curing and testing of adobe specimens are given.

A nondestructive test method, based on measuring the penetration resistance of adobe, was found to give reliable predictions of the compressive strength and moisture content of adobe specimens.

Key Words: Adobe; adobe soil; compressive strength; creep; flexural strength; mechanical properties; moisture; non-destructive testing; preservation.

Table of Contents

Table of Contents (Continued)

1. INTRODUCTION

The National Bureau of Standards has been carrying out a project for the National Park Service on the preservation of historic abode structures. Part of this project is concerned with the mechanical properties of abode and the effect of moisture.

1.1 BACKGROUND AND PURPOSE

In a review of abode preservation technology, Clifton [1]*noted that most of the mechanical properties of abode are not well-characterized. Most of the past work has been concerned with measuring the ultimate compressive strength of abode [2-6], and with determining the effects of different soils, mix proportions and specimen sizes on compressive strength [2-4, 7]. Little information has been reported on the creep of either wet or dry abode, or on relationships between compressive strength and the moisture content of abode. The present study was undertaken to obtain needed information on the mechanical properties of abode and to develop relationships between moisture and these mechanical properties.

1.2 PROJECT SCOPE

Three main areas were addressed in the investigation, which are (1) methods for preparing and testing abode specimens, (2) the mechanical properties of abode and the effects of moisture on their values, and (3) nondestructive testing of abode. Standard methods have not been established for the preparation and testing of abode specimens. Therefore, the procedures used at the National Bureau of Standards' (NBS) laboratory are given in detail in Section 2. The mechanical properties of abode which were characterized are compresive and flexural strengths, and creep (Sections 3-5). A nondestructive method developed for predicting the compressive strength and moisture content of abode is described in Section 6.

2. TEST SPECIMENS AND TESTING PROCEDURES

2.1 MATERIALS

Abode materials were obtained from Escalante Ruin and Tumacacori National Monument, which are located in Arizona. Escalante Ruin is the remains of a prehistoric Indian farming community, constructed from earth, located along the Gila River. This site was occupied for several centuries between 900 to 1500 A.D. The abode material from Escalante Ruin was taken from the wall of a dwelling unit. Tumacacori National Monument consists of a mission church, San Jose de Tumacacori, and service buildings. These structures were constructed from abode by Franciscan priests in the earlv 19th century. The existing

*Numbers in brackets refer to references at the end of the report.

buildings at Tamacacori are being preserved in their present condition and abode samples in the needed amount could not be removed from them. Test material, therefore, was taken from the grounds of the site.

The abode soils were shipped to the NBS facilities at Gaithersburg, Maryland, in several 55 gallon (200 litre) drums. Upon arrival, all of the material from each site was blended. Then the soils were fractionated using a 1/4 inch (4.75 mm) sieve. The material passing through the 1/4 in (4.75 mm) sieve was used in the preparation of test specimens.

The physical properties (Table 1) of the test materials were measured following the methods given in Reference 8. The mineralogical compositions of the test materials have been previously reported [9] and are summarized in Table 1.

The soil from the Tumacacori area is reicher in silt (26%) and clay (24%) than that found in abode samples from the church at Tumacacori (silt, 8 to 12%; clay, 8 to 12%) [9]. This is greater than that found in the range characteristic of duable abode (20 to 30% combined silt and clay) [1]. Sand was added to the soil to simulate the abode in the Tumacacori church and to determine the effect of reducing the silt and clay contents on compressive strength. Graded sand, meeting the specifications of ASTM C-109 [10] was added to and blended with the Tumacacori soil on an equal weight basis. The silt and clay contents of this mixture were 18% and 31%, and this mixture is termed "Tumacacori and Sand" in this report.

2.2 AMOUNT OF MIXING WATER

The amount of water needed to make a workable paste and wellconsolidated specimens was determined by making trial mixes. In the first trial mix, the water contents corresponding to the liquid limit was used. Usually the amount of water found necessary to prepare a workable paste was less than the liquid limit. The probable reason for this water reduction is as follows. In making the determination of the liquid limit, soil particles larger than 425 μm are removed. However, the abode soils which have been used to make test specimens in the NBS laboratory contained some particles which were larger than 425 μm and only those particles larger than 4.75 mm were removed prior to making specimens. Particles larger than 425 μm usually absorb much less water than clay-size particles and the reduction in the amount of mix water from the liquid limit value was found to be roughly proportional to the percentage of material larger than 425 μm. For example, the amount of water used in making Tumacacori and Sand specimens (15%) was roughly one half of the liquid limit of the Tumacacori soil (36.5%).

TABLE 1. PHYSICAL PROPERTIES AND MINERAL COMPOSITIONS OF ADOBE SOILS

PROPERTIES[1]	TUMACACORI SOIL	ESCALANTE ADOBE
Soil color name	Dark grayish brown	Pinkish gray
Munsell color notation	10 yr 4/2	7.5 yr 7/2
Particle size distribution:		
Gravel (72 mm)	2%	-----
Sand (.02-2mm)	24%	18%
Silt (2 μm-20 μm)	26%	55%
Clay (<2 μm)	46%	27%
Liquid limit	36.5%	32.9%
Plastic limit	20.7%	21.8%
pH	8.75	8.19
MINERAL COMPOSITION[2]		
Sand	Feldspars>quartz>mica	Quartz>feldspar>calcite
Silt	Quartz>feldspar>mica	Calcite>mixed layer of minerals predominately illite, quartz and feldspars
Clay	Quartz>illite>montmorillonite	Calcite>mixed layer of minerals predominately illite and quartz

1 Properties were measured using the methods given in reference 8.

2 From reference 9.

The feasibility of using a flow table of the type used for cement mortars [11] to determine the required amount of mix water was explored. Based on a few flow determinations it appeared that the flow technique could be used for this purpose. However, the adobe soils were found to corrode the metal table top and this approach was not investigated further.

2.3 PREPARATION OF TEST SPECIMENS

Adobe soils and water were usually mixed in an electrically driven mechanical mixer of the epicyclic type with a capacity of 1.25 gallons (4.73 liters), used for mixing cement paste and mortars. The mixer met the specifications of ASTM C-305 [12]. When large amounts of material were required, a 5.0 gallon (18.9 litre) capacity rotary mixer was used.

The procedure used for preparing adobe soil and water mixtures is as follows:

(1) Place all the soil in the mixing bowl.

(2) Start the mixer and slow add the water over a one minute period. If the mixer has variable speed control, mix at low speed.

(3) Mix for two minutes.

(4) Stop the mixer and scrape down into the batch any soil which may have collected on the side of the bowl.

(5) Finish by mixing for two additional minutes. If the mixer has speed control, use medium speed.

The method of molding test specimens is similar to that used for preparing cement mortar specimens and is described herein. Immediately after preparing an adobe soil batch, it was placed into specimen molds which were previously lightly oiled with 20-30 weight motor oil. Each mold was held filled with abode and the abode was tamped 12 times with a hard rubber tamper having a flat tamping face of 1/2 by 1 inch (13 by 25 mm) cross section. Then the mold was filled with a second layer which was tamped until the abode was well compacted. Finally, the abode protruding above the top of the mold was removed by drawing the flat side of a trowel across the top of the mold and the face of the specimen was leveled with the trowel.

After molding, specimens were exposed to laboratory air (approximately 70°F (21°C) and relative humidity between 30 to 50%) until they were removed from the molds. Unless early age strength data was desired, the specimens were allowed to harden for 48 hours before being removed from the molds. Exploratory studies were undertaken to determine the effect of specimen size on the measured compressive strength. Specimen

cube sizes of 2 inch (50 mm), 4 inch (102 mm), and 6 inch (154 mm) were used. However, the 4 inch (102 mm) and 6 inch (154 mm) cube specimens dried very slowly in the molds and often did not retain their shape if removed within a week after casting. Therefore, 2 inch (50 mm) cube specimens were used exclusively for compressive strength determinations and also in creep studies.

2.4 MEASUREMENT OF COMPRESSIVE AND FLEXURAL STRENGTHS

The compressive strength of 2 inch (50 mm) cubes was measured following the methods of ASTM-C109 [10]. The load was applied at a rate so that the maximum load was reached between 20 to 80 seconds after start of loading.

Drying shrinkages of up to 7 percent were measured for abode specimens. Such a shrinkage results in approximately a 14 percent reduction in the surface area of a 2 inch (50 mm) cube. Therefore, if the linear dimensions of a specimen are not measured and are assumed to be 2 inch (50 mm), the calculated compressive strengths could be substantially less than the actual strength. The dimensions of the loading and bearing faces of compressive test specimens should be measured and their average value used in calculating compressive strengths.

The flexural stength of 1.575 by 1.575 by 6.3 inch (40 by 40 by 160 mm) prism specimens was measured using the methods of ASTM C-348 [14]. Measurements of the flexural strengths of abode prisms were not found to be highly reproducible (Section 3.2) and no corrections for specimen shrinkage were made.

2.5 MEASUREMENT OF MOISTURE CONTENTS

The moisture contents of abode specimens were measured by the procedure given in ASTM D-2216 [14]. Specimens were dried in a drying oven at 230 °F (110 °C) to a constant weight. In most cases, constant weight was obtained in 24 hours. Samples were allowed to cool to room temperature before being weighed. Moisture contents were calculated on the basis of the dry weight of samples by the following equation:

$$\text{Moisture contents (\%)} = \frac{\text{Weight of wet soil} - \text{Weight of dry soil}}{\text{Weight of dry soil}} \times 100$$

3. COMPRESSIVE AND FLEXURAL STRENGTHS OF DRIED ADOBE

The maximum compressive strengths of the three abode specimens and the flexural stengths of two of the adobe were measured and are given in this section. In addition, results of an exploratory study on the effects of drying temperature and age on the compressive strength of the Escalanate adobe are presented.

3.1 MAXIMUM COMPRESSIVE STRENGTHS

The maximum compressive strengths measured in the present study for Tumacacori soil, Tumacacori and Sand and Escalante adobe specimens are listed in Table 2. Note that the Escalante adobe specimens were conditioned differently than those of the other two adobe systems. The order of the maximum strengths is Tumacacori soil > Tumacacori and Sands > Escalante. This sequence does not appear to correlate well with the differences between the physical properties of the adobe systems and probably can be attributed to differences in the chemical and mineralogical compositions of the Tumacacori soil and Escalante adobe. The closeness of the values for the Tumacacori soil and Tumacacori and Sand specimens suggests that even when the particle size distribution of the Tumacacori soil was adjusted by adding sand, sufficient clay and silt was still present to form a matrix in which the sand particles of the Tumacacori and Sand adobe were firmly embedded [1].

3.2 FLEXURAL STRENGTHS

The flexural strengths of the Tumacacori soil and Escalante adobe were measured using the methods described in Section 2.5. Specimens were prepared using water/soil ratio of 0.30 for Tumacacori soil and 0.25 for Escalante adobe. They were stored under laboratory conditions and tested at 14 days.

The average flexural strength of the Tumacacori soil specimens was 60 psi (0.41 MN/m^2) and 34 psi (0.23 MN/m^2) for the Escalante adobe. Their respective standard deviations (S.D.) were 17 psi (0.11 MN/m^2) and 7 psi (0.05 MN/m^2). These flexual strengths are in the range of those reported by others [2-4].

3.3 EFFECT OF DRYING CONDITIONS ON COMPRESSIVE STRENGTH

Freshly prepared adobe bricks are usually slowly cured (allowed to harden) by being exposed to sunlight or to a dry atmosphere at ambient temperature. An exploratory study was carried out to ascertain the effects of two drying temperatures and the length of the drying period on the compressive strength. Escalante adobe was used for this study and the results are given in Table 3.

An increase in compressive strength with curing age was found for specimens cured at 70 °F (21 °C); while the strength of specimens cured at 140 °F (60 °C) first increased and then decreased with age. Both Webb et al. [5] and Patty [7] also observed that the compressive strength of earth bricks increased with age when cured at ambient temperatures. The decrease in strength of specimens cured at 140°F (60°) possible was caused by some phase or mineralogical change in the adobe.

TABLE 2 MAXIMUM MEASURED COMPRESSIVE STRENGTHS 1/

MATERIAL	COMPRESSIVE STRENGTH PSI 2/	S.D 3/	(MN/m^2)	(S.D)	WATER/SOIL RATIO	CURING CONDITIONS
1. Tumacacori soil	617	76	(4.25)	(0.52)	0.30	180 days at about 70 °F (21 °C) and relative humidity near 0.
2. Tumacacori and Sand	571	44	(3.94)	(0.30)	0.15	180 days at about 70 °F (21 °C) and relative humidity near 0.
3. Escalante adobe	312	18	(2.15)	(0.12)	0.25	2 days at 140 °F (60 °C) in an oven.

1/ Compressive strengths of 2 in. (50 mm) cubes were measured.

2/ Average of 5 specimens.

3/ S. D. denotes standard deviation.

TABLE 3. EFFECT OF DRYING TEMPERATURE ON COMPRESSIVE STRENGTH OF ESCALANTE ADOBE SPECIMENS[1/]

AGE (DAYS)	COMPRESSIVE STRENGTHS[2/] PSI	S.D.[4/]	(MN/m^2)	(S.D)	MOISTURE CONTENTS[3/] PERCENT	S.D.
			Specimens dried at 70 °F (21 °C)[5/]			
7	221	17			2.77	0.20
14	261	25			2.50	0.27
28	286	22			2.06	0.25
35	295	35			Not measured	
			Specimens dried at 140 °F (60 °C)			
1	258	44			2.63	0.16
2	312	18			2.38	0.09
3	281	28			2.19	0.12
4	253	40			1.98	0.17

[1/] Two inch (40 mm) cubes were tested.

[2/] Between 3 and 6 specimens were tested at each condition.

[3/] Moisture contents measured after specimens were tested in compression. Specimens were prepared using a water to soil weight ration of 0.25.

[4/] S.D. denotes standard deviation.

[5/] Relative humidity in the range of 30 to 50 percent.

This brief study indicates that standard curing conditions must be established and used if results from the strength testing of adobes are to be compared.

4. EFFECT OF MOISTURE ON COMPRESSIVE STRENGTH OF ADOBE

Among the major factors thought to be responsible for the deterioration of adobe is the loss of compressive strength caused by the presence of excess moisture [15]. Excess moisture is defined by the present authors as a moisture content which is greater than the equilibrium moisture content of sun-dried adobe. The equilibrium contents of sun-dried adobe brick vary with their clay content but usually are in the range of 1 to 3 precent [2,4,5]. As previously discussed (Section 1) the effects of moisture on the strength of adobe have not been well studied.

The effects of absorption of rain and ground water, exposure to a wide range of relative humidities, and wet and dry cycles on the compressive strength of adobe were explored.

4.1 EFFECT OF ABSORPTION OF RAIN AND GROUND WATER

Adobe can absorb appreciable quantities of rain and ground water which is believed to reduced its compressive strength [15]. However the extent of such strength losses have not been reported. Relationships between excess moisture and strength of adobe were investigated in the present study by measuring the strength of partially dried specimens, i.e. they contained a portion of their mix water.

4.1.1 Method of Testing

Tumacacori soil and Escalante adobe specimens were prepared using amounts of mixing water equivalent to their liquid limits 36.5% and 32.9%, respectively (Table 1). Tumacacori and Sand specimens were prepared using a water/soil ratio of 0.15, by weight.

The compressive strengths and moisture contents of 2 inch (50 mm) adobe cubes were periodically measured by starting within 24 hours after their formation. Specimens were dried under laboratory conditions, 70°F (21°C), relative humidity between 30 and 50%. By this method, a broad range of moisture contents was obtained. After specimens were tested in compression, they were immediately placed in preweighed (tared) jars, which were tightly sealed. Then their moisture contents were measured by the methods described in Section 2.6.

4.1.2 Discussion of Results

Results are shown in Figure 1 for specimens made from Escalante adobe, Tumacacori soil, and Tumacacori and Sand. Compressive strength of all the systems rapidly decreased from their maximum measured values with increases in moisture content. The highest moisture content plotted for each material was close to the moisture content at which specimens began to sag and deform. The moisture region between 2 and 10% is of particular interest because almost all of the moisture measurements taken on the adobe of San Jose de Tumacacori Church [16] lie within this region. Within these general moisture limits, the compressive strength of Tumacacori soil specimens decreased from 230 psi (1.58 MN/m^2) to 94 psi (0.65 MN/m^2), a change of 59%, and the strength of Tumacacori and Sand specimens decreased from 350 psi (2.4 MN/m^2) to 53 psi (0.37 MN/m^2), or by 84%. Within the same moisture region the compressive strength of Escalante adobe specimens decreased from a maximum of 250 psi (1.7 MN/m^2) to 90 psi (0.62 MN/m^2), a decrease of 64%. Both Tumacacori soil and Escalante adobe specimens have small residual strengths, approximately 30 psi (0.21 MN/m^2), at their respective plastic limits of 20.7% and 21.8%.

4.1.3 Example of Application of Compressive Strength Versus Moisture Relationships

The impact of moisture on the structural stability of the Church at Tumacacori can be estimated if both the loading factors and the relationship between compressive strength and moisture are known. In a structural analysis of the church, Fattal [17] estimated that the maximum compressive load on the adobe was around 20 psi (0.14 MN/m^2). If a safety factor of 2.5 is desired then the strength of the adobe should not be less than 50 psi (0.34 MN/m^2).

The Tumacacori and Sand system is fairly representative of the "average adobe in the church, so that its strength versus moisture relationship will be used in the present analysis. As previously observed, the compressive strength of the Tumacacori and Sand adobe was greater than 50 psi (0.34 MN/m^2) as long as its moisture content was less than 10%. If a higher safety factor is though to be necessary, the permissible amount of moisture can be obtained from Figure 1. For example, a safety factor of 5 is equivalent to a strength demand of 100 psi (0.69 MN/m^2). The compressive strength of the Tumacacori and Sand adobe is above this value as long as its moisture contnet does not exceed 5%.

The purpose of the preceding analysis was to demonstrate a procedure for estimating if moisture in an adobe wall is likely to impair its structural resistance. Application of these results to other adobe structures should only be done if the adobe materials have the same response to moisture as the materials used in this study.

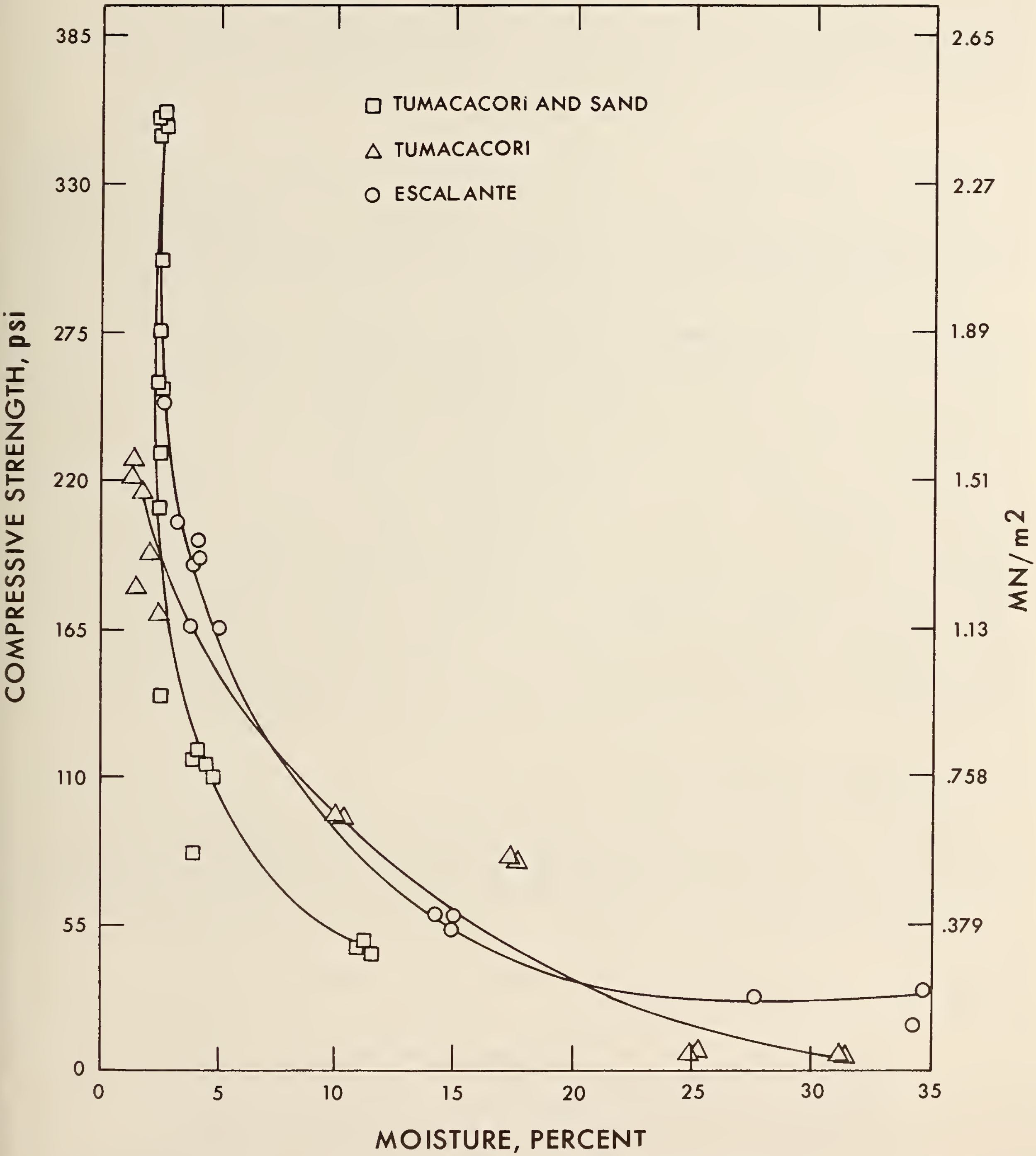

Figure 1. Effect of moisture contents on the compressive strength of adobe. Compressive strength of adobe moisture contents were calculated on the basis of the dry weight of samples.

4.2 EXPOSURE OF ADOBE TO A WIDE RANGE OF RELATIVE HUMIDITIES

Adobe specimens were exposed to a wide range of humidity conditions for the purpose of ascertaining the effects on adobe strength of (1) exposure to different humidities, and (2) prolonged exposure to constant relative humidities.

4.2.1 Method of Testing

Adobe specimens were prepared using the following water/soil ratios: 0.30 for Tumacacori soil; 0.15 for Tumacacori and sand; and, 0.25 for Escalante adobe.

The specimens were allowed to dry at laboratory conditions for 14 days, then oven-dried at 131 °F (55 °C) for 24 hours. As soon as the specimens had cooled to ambient temperature, they were weighed. Then the specimens were placed in 4.5 gallon (17 liter) glass containers which had a diameter of 12 inches (305 mm) and height of 12 inches (305 mm). The containers were sealed with 0.5 inch (12.7) thick plastic plates (Figure 2). Constant relative humidities were maintained in each container by placing in the bottom of the containers one of the following: a dessicant, a saturated aqueous solution of a suitably chosen salt, or pure water (Table 4). The containers were periodically agitated to ensure that constant relative humidities were being maintained. Containers were opened only when specimens were removed for testing. The amount of moisture absorbed and the compressive strength of specimens were measured after specimens had been exposed to constant humidities for 60, 120 and 180 days.

4.2.2 Discussion of Results

The change in moisture content and in the compressive strength of adobe specimens exposed to relative humidities of 0, 10, 56, 79 and 100 percent are shown in Figures 3 - 8. Each data point is the average of between 3 to 5 measurements.

An analysis of the moisture gain versus relative humidity curves (Figures 3 - 5) indicates that:

(1) Regardless of the exposure time, the Tumacacori soil and Escalante adobe systems absorbed increasingly larger amounts of moisture as the relative humidity increased. In contrast, the Tunacacori and Sand system absorbed little moisture in the range of 0 to 60% relative humidity, and only in higher humidity region was an an appreciable moisture increase measured.

(2) The relative affinity for moisture in the region below 80% relative humidity was roughly: Tumacacori soil > Escalante adobe > Tumacacori and Sand. This order is in the same sequence as that based on the clay contents of the materials (Table 1). In the region above 80% relative humidity, the moisture affinity of the Escalante adobe increased more rapidly than that of the other systems.

(3) Small moisture fluctuations are evident when the curves obtained after 180 days are compared with those at 120 days. This indicates that the moisture contents of the adobe specimens did not reach complete equilibrium after 120 days and possible did not even after 180 days of exposure.

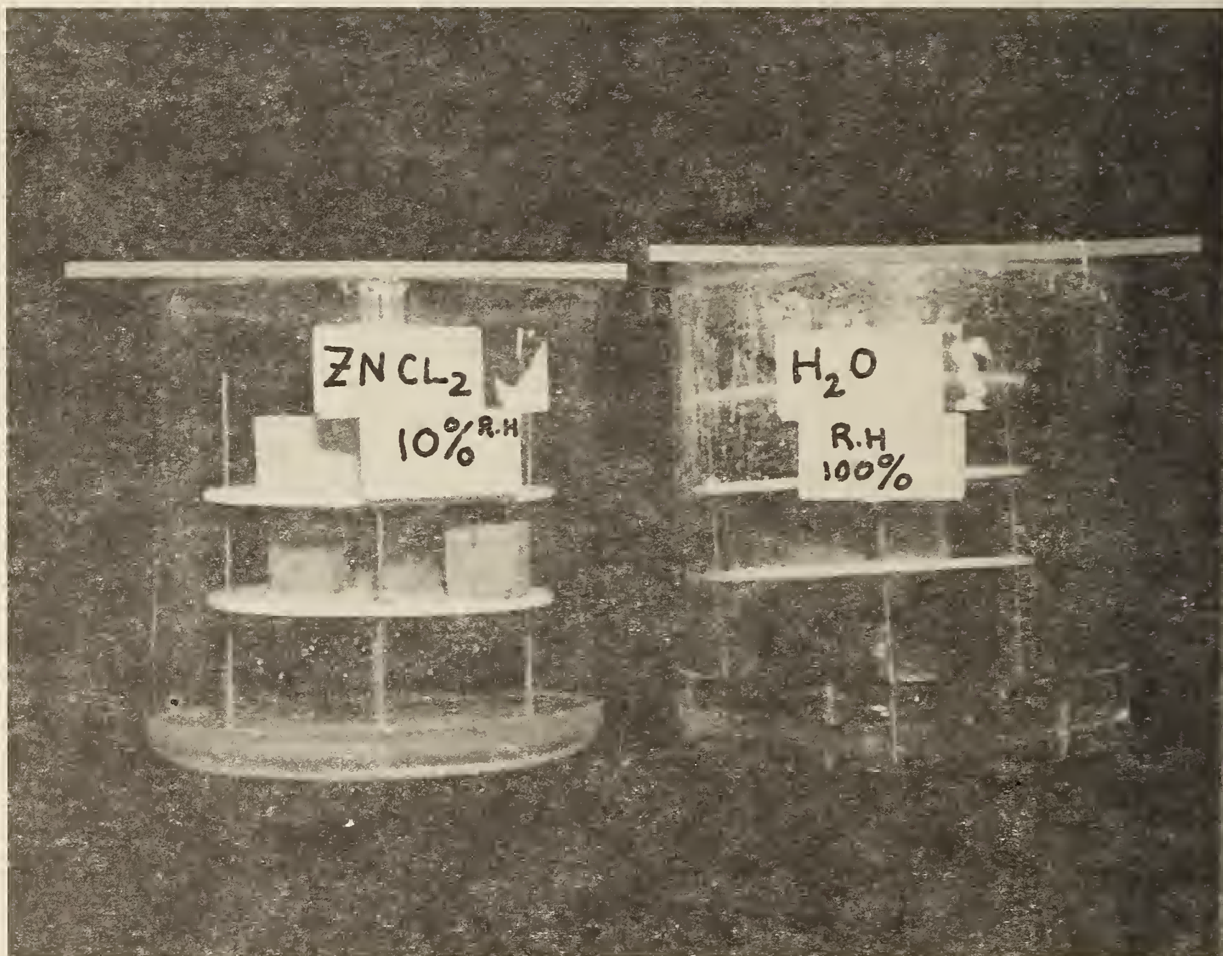

Figure 2. Adobe specimens exposed to constant relative humidities.

TABLE 4. MATERIALS USED FOR OBTAINING CONSTANT HUMIDITIES

MATERIAL	% RELATIVE HUMIDITY [1/] AT 68 °F (20 °C)
Anhydrous $CaSO_4$	0
$ZnCl_2$ 1.5 H_2O [2/]	10
$Ca(NO_3)_2$ 4 H_2O	56
$NaC_2H_3O_2$ 3 H_2O [2/]	76
Water	100

[1/] Values taken from:

(1) Lange's Handbook of Chemistry, Editor-John A. Dean, 11th edition (McGraw-Hill Book Company, N.Y., 1973)

(2) R.H. Stokes and R.A. Robinson, Standard Solutions for Humidity Control at 25 °C, Industrial and Engineering Chemistry <u>41</u> (9), 2013 (1949)

(3) Handbook of Chemistry and Physics, 50th edition (The Chemical Rubber Company, Cleveland, 1970)

[2/] Saturated aqueous solution.

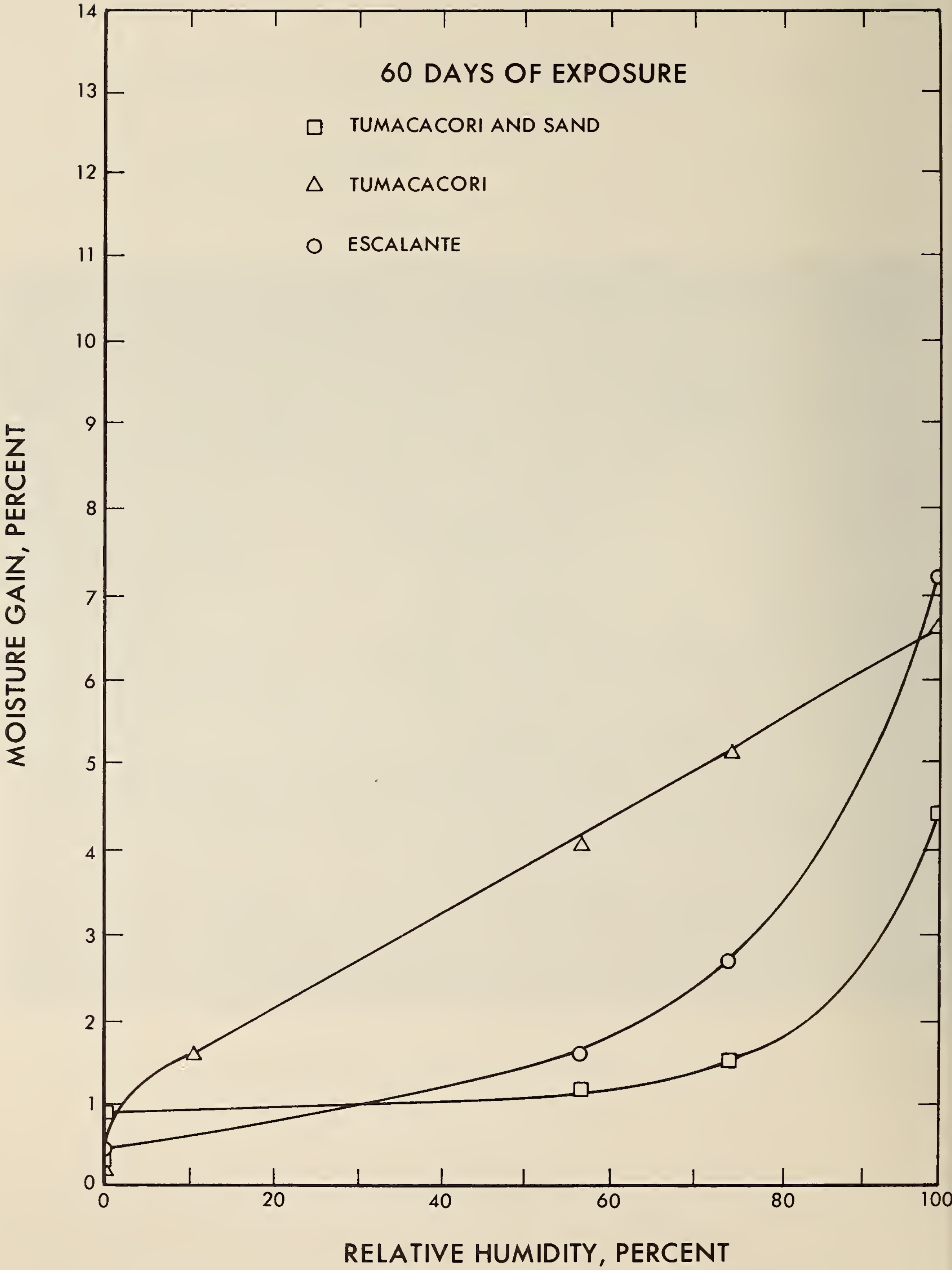

Figure 3. Moisture gain of adobe specimens exposed to different relative humidities for 60 days.

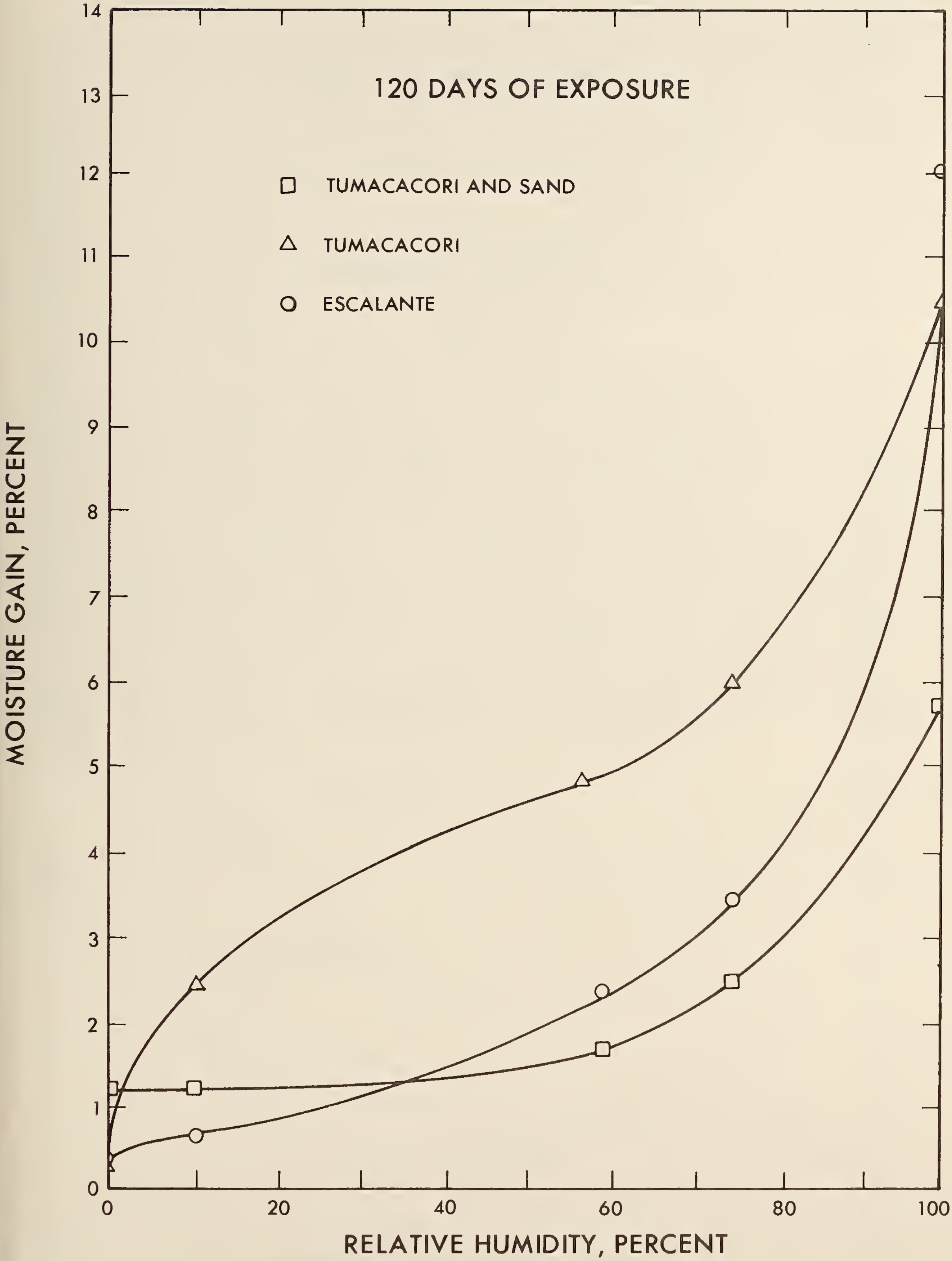

Figure 4. Moisture gain of adobe specimens exposed to different relative humidities for 120 days.

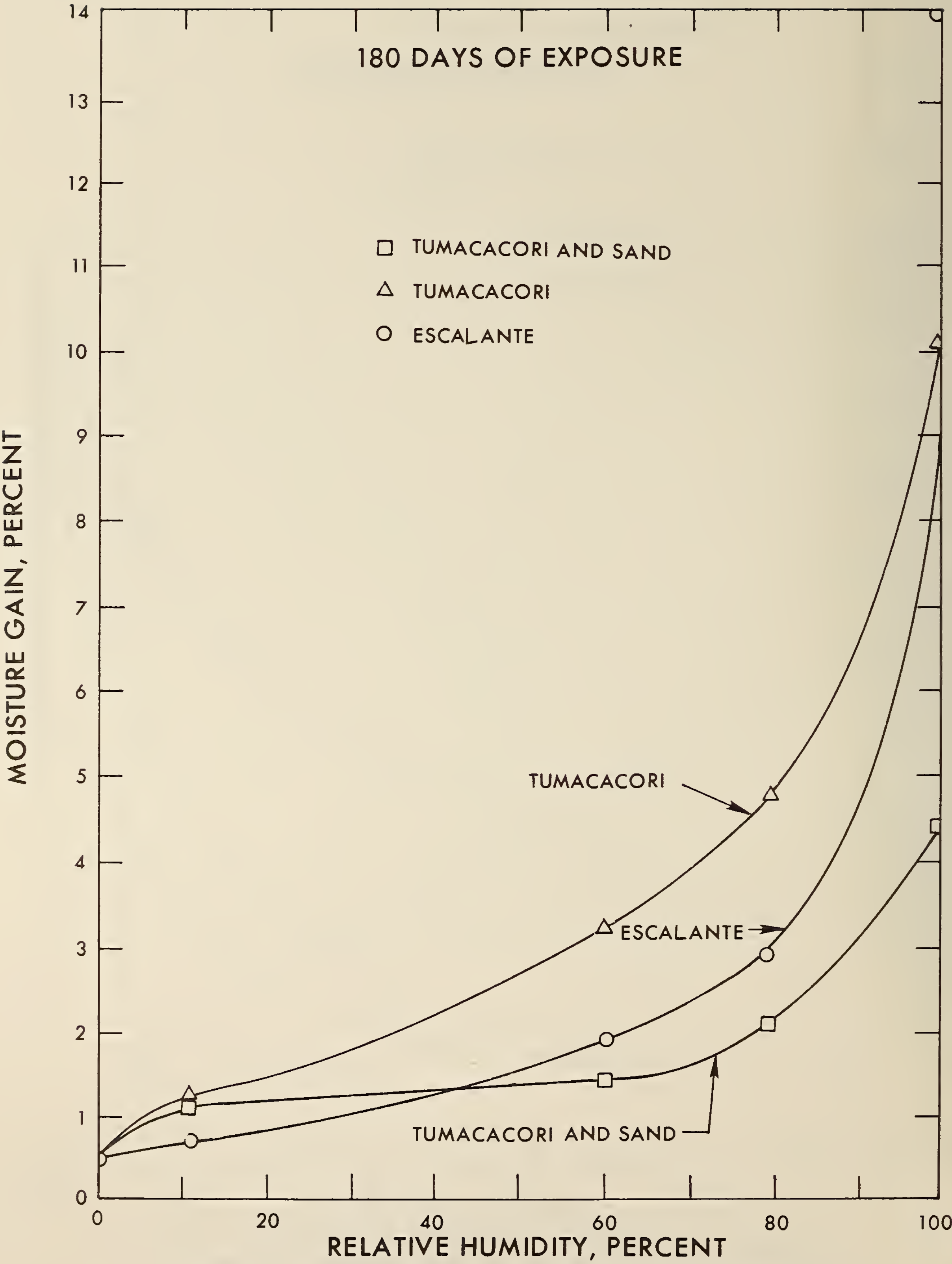

Figure 5. Moisture gain of adobe specimens exposed to different relative humidities for 180 days.

Comparison of the relationships between compressive strength and relative humidity (Figures 6 - 8) for the three abode systems indicates that they have some similar characteristics in their response to relative humidity. For example, their strengths decreased sharply between 0-10% relative humidity, a more gradual decrease occurred between 10 and 60% relative humidity, and then an appreciable decrease in strength took place when the relative humidity was above 60%. However, even with a relative humidity as high as 80%, the compressive strengths of the three adobes were above 100 psi (0.68 MN/m^2). In addition, it was observed that while the strengths of the specimens were lower at 120 days of exposure than at 60 days, their strengths were generally higher after 180 days.

The negative effect of increasingly higher relative humidity on the compressive strength of adobe is clearly attributable to an increase in moisture content. However, the adobe system, Tumacacori soil, which exhibited in greatest affinity for moisture, also had the highest strength over the complete humidity range. Another peculiarity is the closeness of strength versus relative humidity curves for the Tumacacori and Sand and the Escalante adobe systems, which almost coincide at 180 days, despite the noticeable differences in their moisture versus relative humidity curves. Possibly, differences in the clay mineralogy of the two systems is manifested more in their affinity for moisture than in their compressive strengths. It does appear that the major factor controlling the response of the three adobes to relative humidity is their clay contents. The compressive strengths and moisture affinity of the adobes roughly increased with higher clay content in the sequence: Tumacacori soil $>$ Escalante adobe $\gtrsim$ Tumacacori and Sand.

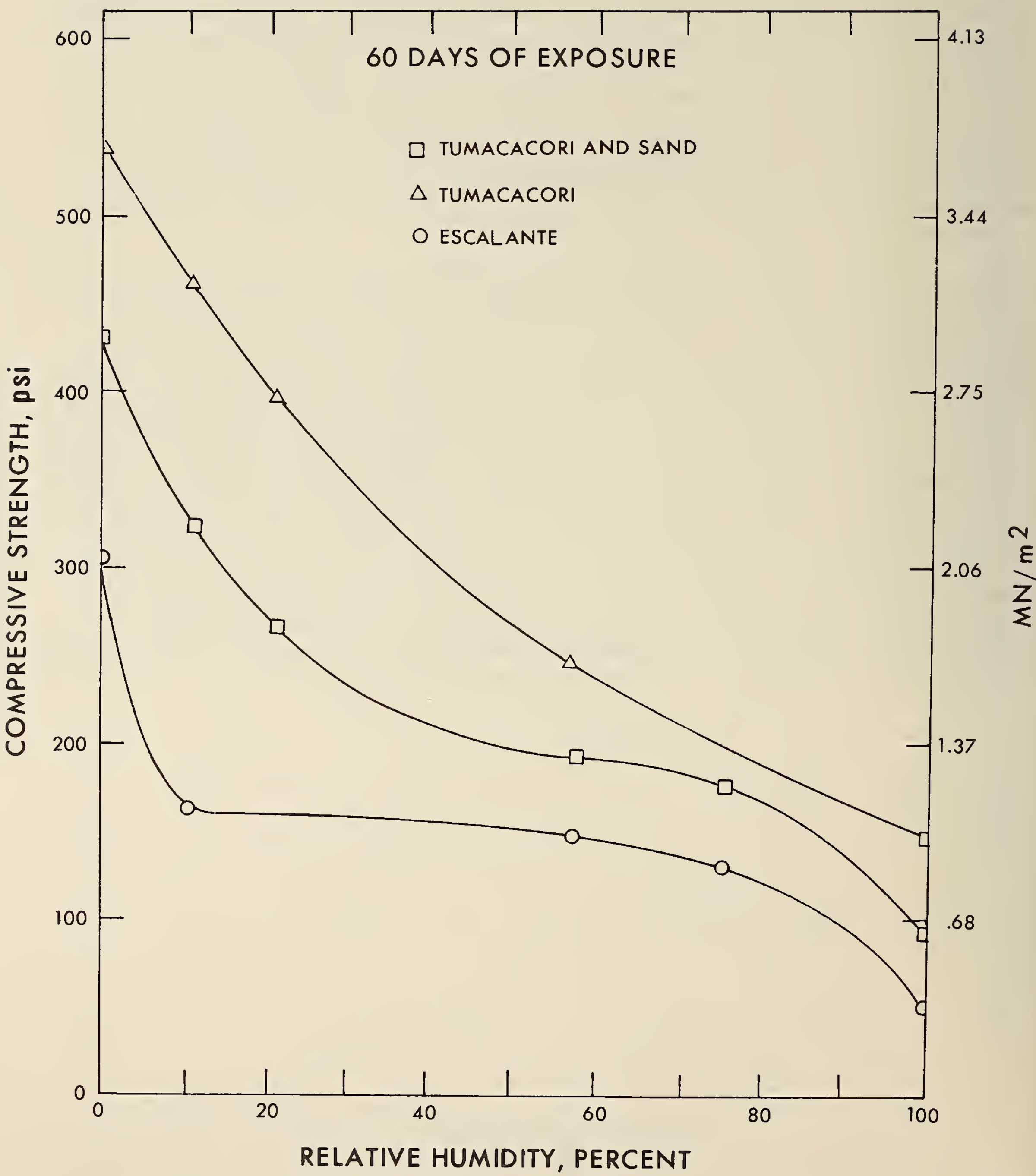

Figure 6. Effect of relative humidity on compressive strength of adobe specimens.

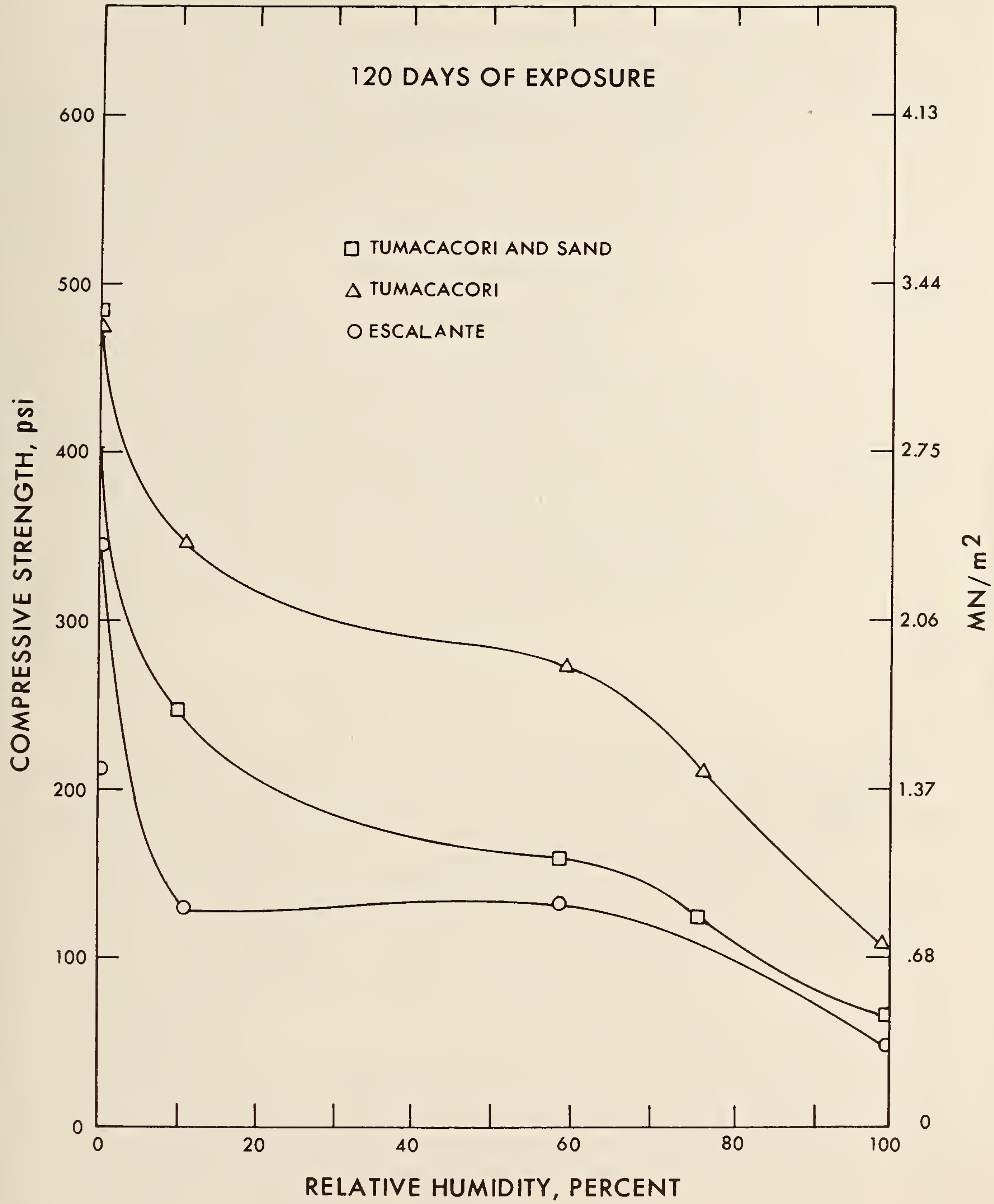

Figure 7. Effect of relative humidity on compressive strength of adobe specimens.

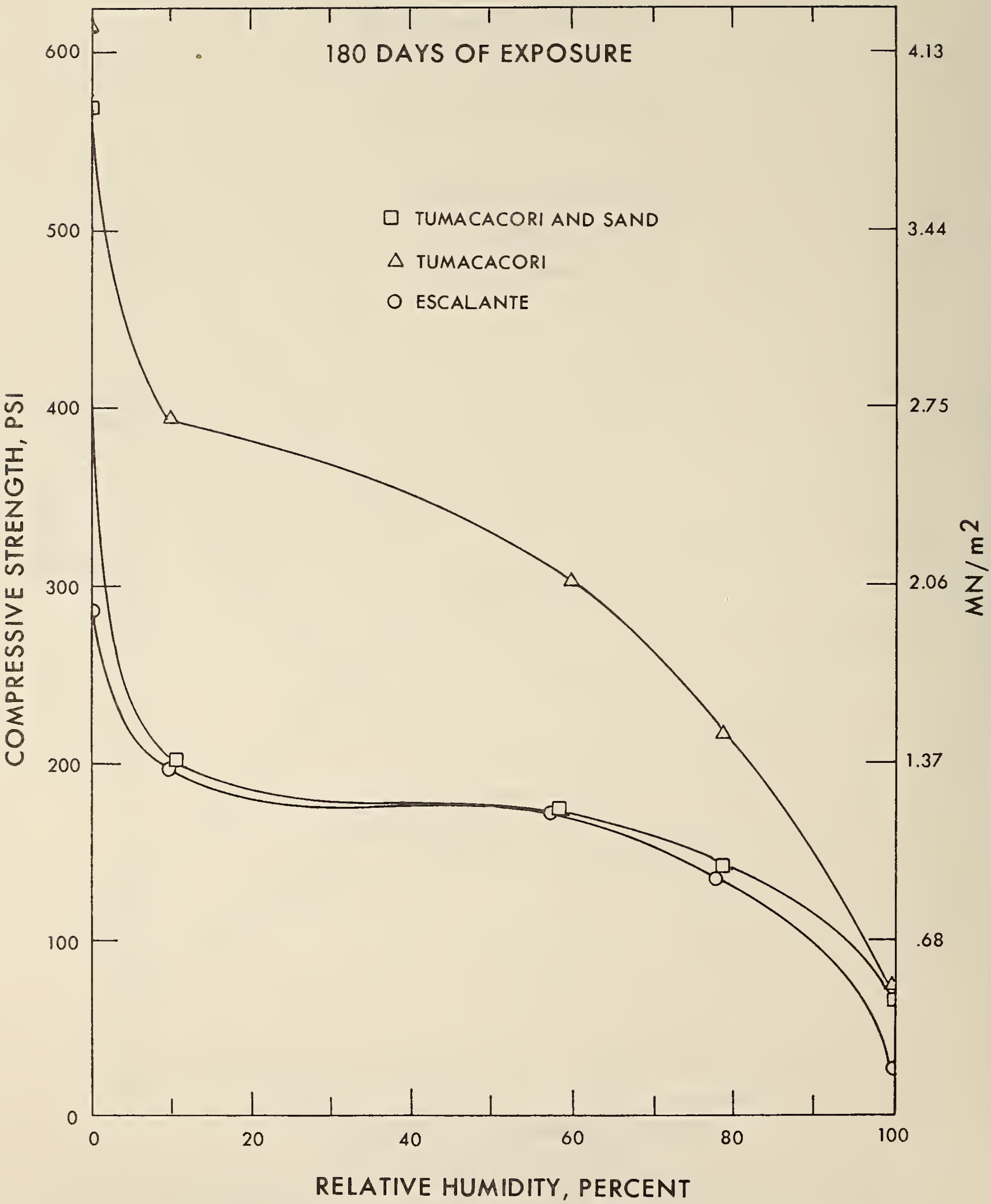

Figure 8. Effect of relative humidity on compressive strength of adobe specimens.

4.3 EFFECT OF WET AND DRY CYCLES ON COMPRESSIVE STRENGTH

Adobe walls will usually swell upon becoming damp and shrink upon drying, which can result in their cracking. It is believed that if wet and dry cycles continue for several years, adobe walls may become so badly cracked that they could collapse [15]. In the present study, the effect of wet and dry cycles were explored by subjecting specimens to conditions which should accelerate the cracking process.

4.3.1 Method of Testing

Adobe specimens were prepared using mix water/soil ratios of 0.30 for Tumacacori soil, 0.15 for Tumacacori and Sand, and 0.25 for Escalante adobe. Specimens were allowed to dry for 7 days under laboratory conditions, and then dried at 221°F (105°C) for 24 hours before being subjected to wet and dry cycles. Specimens were exposed to 122°F (50°C) and 100% relative humidity for 24 hours during the wet cycling. After completion of a wet cycle, specimens were immediately subjected to a dry cycle by being placed in an oven at 221°F (105°C) for 24 hours. The drying process completed a wet and dry cycle.

4.3.2 Discussion of Results

The results (Table 5) clearly indicate that the accelerated wet and dry cycling process has a significant effect on the compressive strength of the adobe specimens. After 7 cycles, the Escalante adobe had a residual strength which was 28% of its original value, and similarly the Tumacacori soil strength was reduced to 26% of its original. In addition, extensive cracking was observed in these specimens. The Tumacacori and Sand system had a greater resistance to the cycling process. For example, after particles, its strength was 258 psi (1.78 MN/m^2) or 49% of its original value. Furthermore, no cracks were observed in these specimens.

The improved behavior of the Tumacacori and Sand system compared to the Tumacacori soil is probably attributable to the decrease in clay content caused by the addition of sand to the soil (see Section 2.1). Several investigators [3,18] have observed that the cracking tendency of abode bricks with high clay content could be reduced by the addition of sand.

Conditions used to accelerate the effects of wet and dry cycles certainly are more severe than those that adobe brick would normally encounter. However, the test results do suggest that adobe may deteriorate when subjected to normal wet and dry cycles. Several years, however, would probably be required for the wetting and drying process to be manifested in the field.

TABLE 5. RESULTS OF WET AND DRY CYCLES ON COMPRESSIVE STRENGTH

NUMBER OF CYCLES[1/]	COMPRESSIVE STRENGTH PSI (MN/m^2)		
	TUMACACORI SOIL	TUMACACORI AND SAND	ESCALANTE ADOBE
0	483 (3.33)	530 (3.65)	303 (2.09)
4	213 (1.47)	337 (2.32)	206 (1.42)
7	124 (0.85)	305 (2.10)	86 (.59)
11	---	258 (1.78)	---

[1/] Wet cycle: 24 hours at 122 °F (50 °C) and 100% relative humidity.

Dry Cycle: 24 hours in oven at 221 °F (105 °C).

4.4 IMPLICATIONS OF COMPRESSIVE STRENGTH AND MOISTURE RELATIONSHIPS

The exploratory studies described herein indicate that both excess moisture and wetting and drying processes can be detrimental to the compressive strength of adobe. The magnitude of the effects of absorption of rain and ground water, exposure to high humidities, and wetting and drying processes will depend on the severity of the conditions. Effects of exposure to high relative humidities may be manifested only over many years. In contrast, penetration of adobe by rain and ground water can have a more immediate effect. In addition, rapid accumulation of moisture in adobe would probably cause a rapid and large expansion, which could be followed by shrinkage cracking as the adobe dries. Probably, the most favorable condition for adobe, besides being dry, is on in which its moisture content remains constant below a critical level.[1/]

The loading on most historic adobe structures is low. For example, for an adobe wall 20 feet (6.1 m) long constructed from adobe brick with a dry density of 125 lb/ft^3 (2000 kg/m^3) [1], the maximum dead weight load stress is 17 psi (0.12 MN/m^2). If the adobe contains an average of 10 percent moisture, the dead load stress is still only 19 psi (0.13 MN/m^2). It is unlikely that an adobe structure located in the arid southewestern region of the United States with a good roof and proper drainage would have and average moisture content as high as ten percent. Therefore, such an adobe structure constructed with a good quality adobe brick would probably not collapse solely because of loss of compressive strength due to excess moisture. In cases where a roof has deteriorated or never existed and proper drainage does not exist, loss of compressive strength due to accumulation of moisture could endanger the structural integrity of adobe structures. Other major deleterious processes of rain water are undercutting at the base of walls, slow erosion of the vertical surfaces of walls [1].

1/ Critical moisture level is defined as the moisture content of an adobe at which an wall is no longer structurally safe.

5. CREEP OF ADOBE

The creep of a soil describes its stress-strain-time (rheological) performance [19]. The creep after construction of an adobe wall is part of the settling compaction process. Settling creep involves particle reorientation and extrusion of air and water from the adobe pores and voids. After the settling process is completed, the creep of adobe under normal loads will probably be infinitesimal as long as it is dry. However, the reentry of moisture into the pores and voids of an adobe could cause further reorientation of particles and swelling of the clay particles. The creep can again take place, its magnitude depending on the amount of moisture and the type of clay in the adobe.

The creep properties of adobe have not been well-characterized. Therefore, an exploratory investigation was carried out to provide information on the creep of adobe and to determine if moisture has an appreciable effect on creep.

5.1 TEST METHOD

Two inch (25.4 mm) cube adobe specimens were prepared using water/soil ratios of 0.30 for Tumacacori soil, 0.15 for Tumacacori and Sand, and 0.25 for Escalante adobe. The specimens were allowed to dry in laboratory air for four weeks prior to testing.

A creep specimen with loading assembly attached is illustrated in Figure 9. Specimens were dead-weight loaded with lead bricks suspended underneath the specimens. The loading assembly was free to move through holes drilled in the supporting platform. Creep of the specimens was measured with 1×10^{-4} inch (2.54×10^{-3} mm) micrometer dial gages. The gages were attached to the top of the loading assembly and gage stems bore on the supporting platform. Creep specimens under test are shown in Figure 10.

Six creep specimens were exposed to a relative humidity close to 100%. The portion of a loading assembly above the platform was completely enclosed in a square shaped glass container attached to the platform with a sealant (Figure 11). A dish containing water was placed under the glass container. Problems were encountered with this setup because of corrosion of the dial gages and reliable data was obtained from only three of the original six specimens.

Specimens were loaded at levels of 21 to 36 psi (.15 to .25 MN/m^2), which are thought to be close to or slightly higher than those encountered in most historic adobe structures.

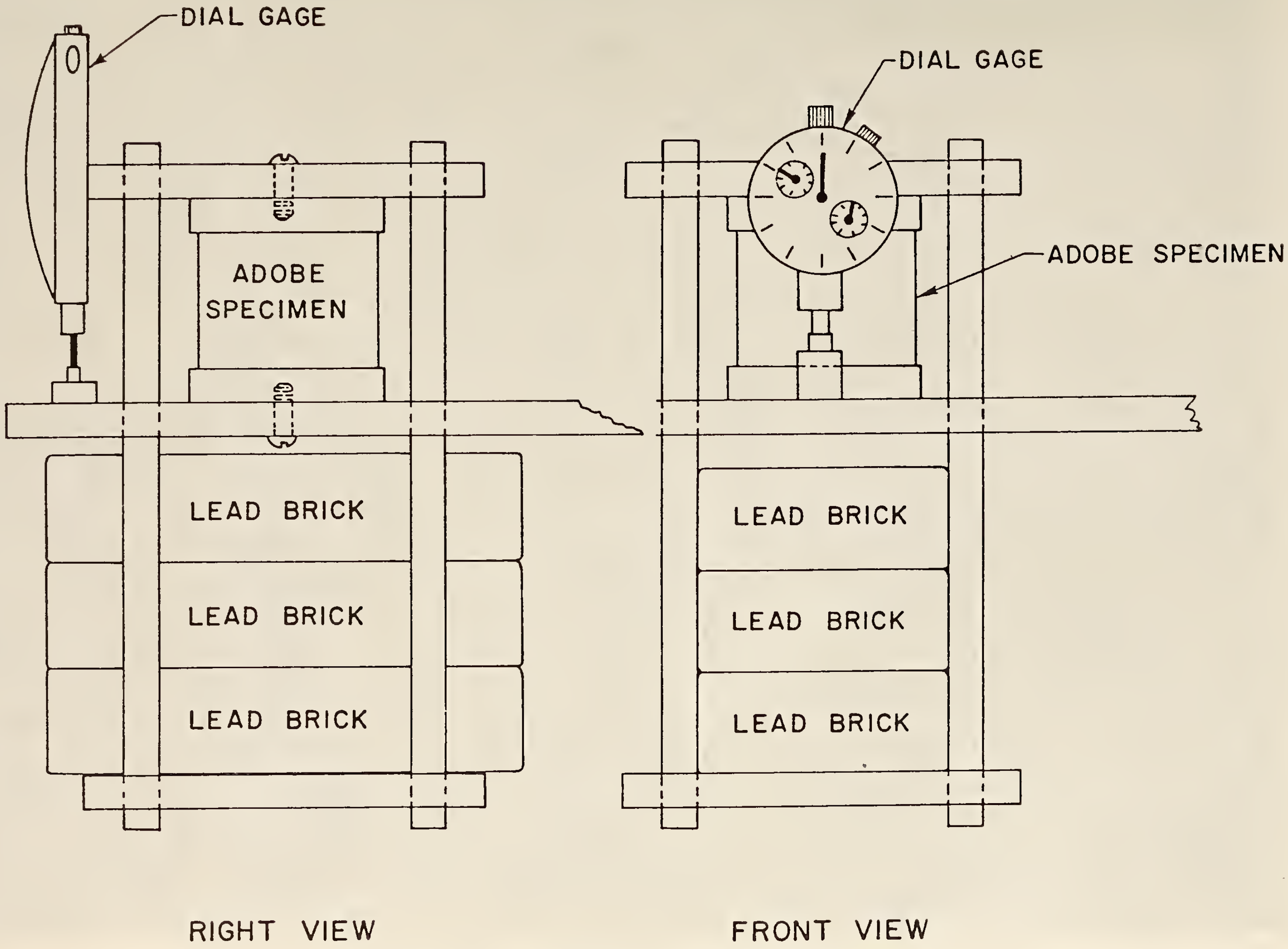

Figure 9. Schematic of creep assembly.

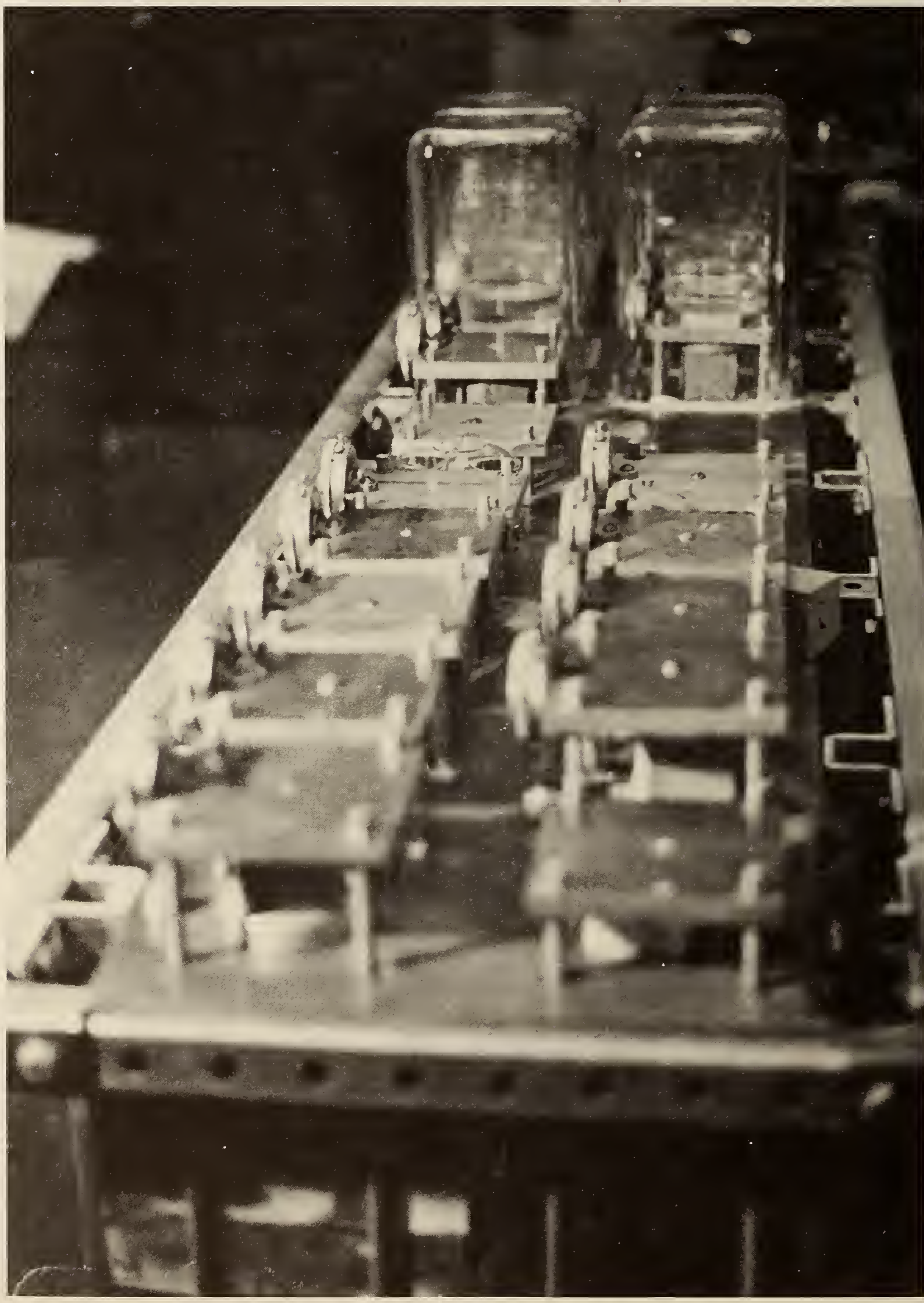

Figure 10. Creep specimens under test.

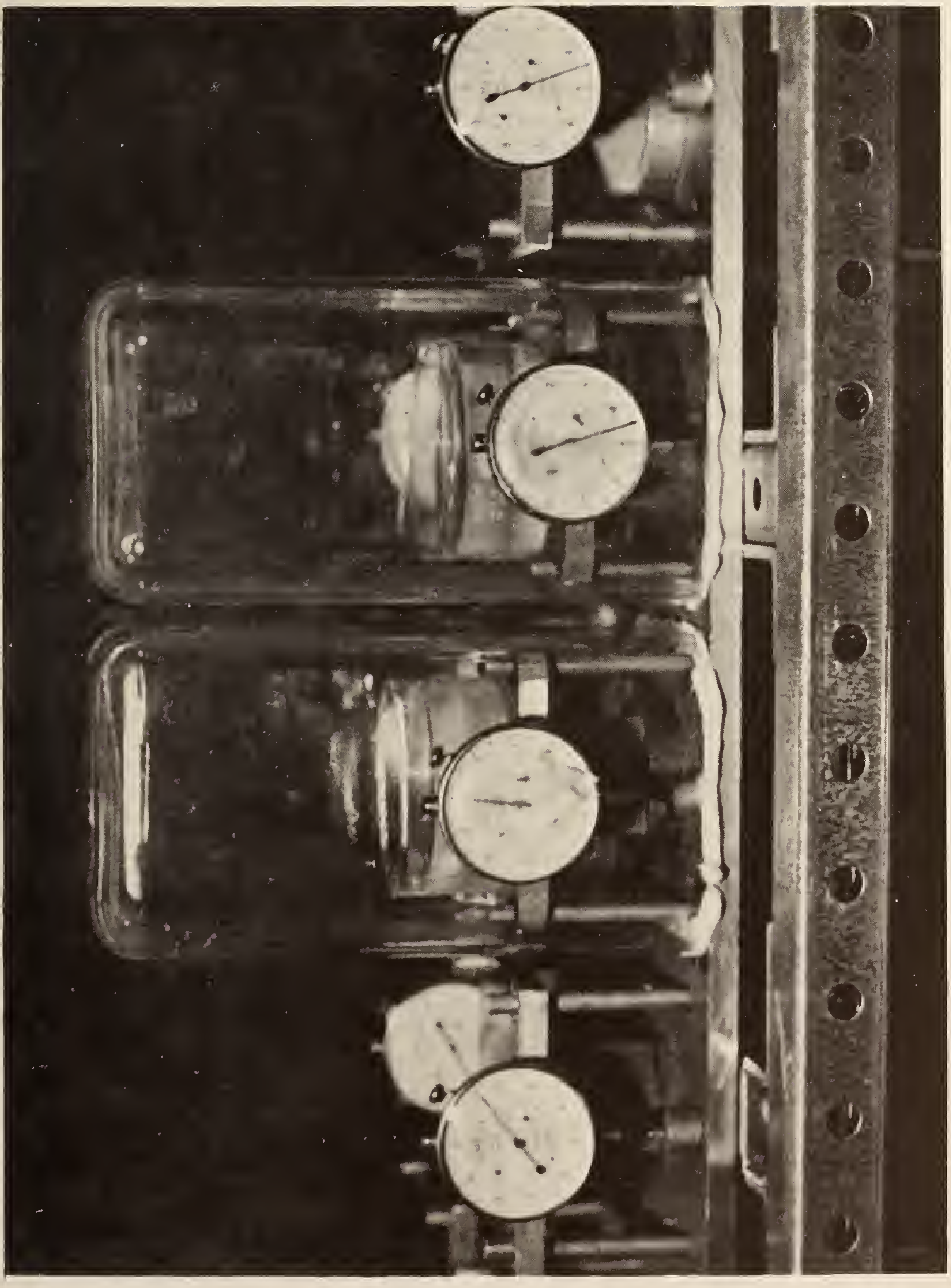

Figure 11. Creep specimens exposed to relative humidity close to 100%.

5.2 DISCUSSION OF CREEP RESULTS

Creep measurement (Table 6) were not closely reproducible but several trends are discernible. The largest amount of creep took place during the first three weeks of testing (Figure 12). This early creep probably can be attributed to compaction of the specimen and possibly is similar to that taking place in the settling of an adobe structure. Little creep was measured after about 7-9 weeks. The effect of increasing the load on creep was more pronounced for the Tumacacori soil than for the Escalante adobe.

The first 11 specimens listed in Table 6 were exposed to relative humidities between 30 and 50% at 70°F (21°C), which are higher than those normally encountered in the arid southwestern region of the United States. However, during rainstorms, humidities higher than 80% have been measured at the Tumacacori National Monument [16]. The last three specimens listed in Table 6 were exposed to relative humidities close to 100%. Creep of those three specimens was more than 200% greater than the creep of specimens exposed to the lower relative humidity.

While the creep data presented herein should not be quantitatively applied to an actual adobe structure, the large effect of moisture on creep is clearly evident. Furthermore, it can be speculated that cycles of wetting and drying can lead to progressive creep.

Table 6. CREEP OF ADOBE SPECIMENS

SPECIMEN NO.	MATERIAL	APPLIED LOAD PSI (MN/m^2)	CREEP % TIME IN WEEKS 1	2	3	7	9	15	17
			RELATIVE HUMIDITY BETWEEN 30 AND 50% TEMPERATURE 70°F (21°C)						
1.	Tumacacori and Sand	21 (.14)	0.565	.605	.645	---1/	.724	---	.725
2.	Tumacacori and Sand	21 (.14)	.0600	.216	.359	---	.395	---	.425
3.	Tumacacori and Sand	21 (.14)	.0810	.683	.941	---	1.190	---	1.191
4.	Tumacacori and Sand	21 (.14)	.685	.691	.791	---	.907	---	.937
5.	Tumacacori soil	21 (.14)	.152	.158	.197	---	.276	---	.311
6.	Tumacacori soil	27 (.19)	0.000	.049	.499	---	.684	---	.689
7.	Escalante adobe	21 (.14)	.005	.271	.316		.385		.405
8.	Escalante adobe	21 (.14)	.010	.350	---	---	---	---	.384
9.	Escalante adobe	21 (.14)	.735	.880	---	---	---	.889	---
10.	Escalante adobe	27 (.19)	.094	.130	---	.309	---	.360	---
11.	Escalante adobe	36 (.25)	.994	1.09	---	1.23	---	1.25	---
			SPECIMENS EXPOSED TO 100% RELATIVE HUMIDITY, TEMPERATURE OF 70°F (21°C)						
12.	Tumacacori and Sand	21 (.14)	.065	.405	1.92	---	2.61	---	2/
13.	Tumacacori soil	30 (.21)	.696	.725	2.90	---	2/		
14.	Escalante adobe	21 (.14)	.741	.815	2.24	---	2.24	---	2/

1/ Dash indicates measurement not made at indicated time.

2/ Dial gage corroded.

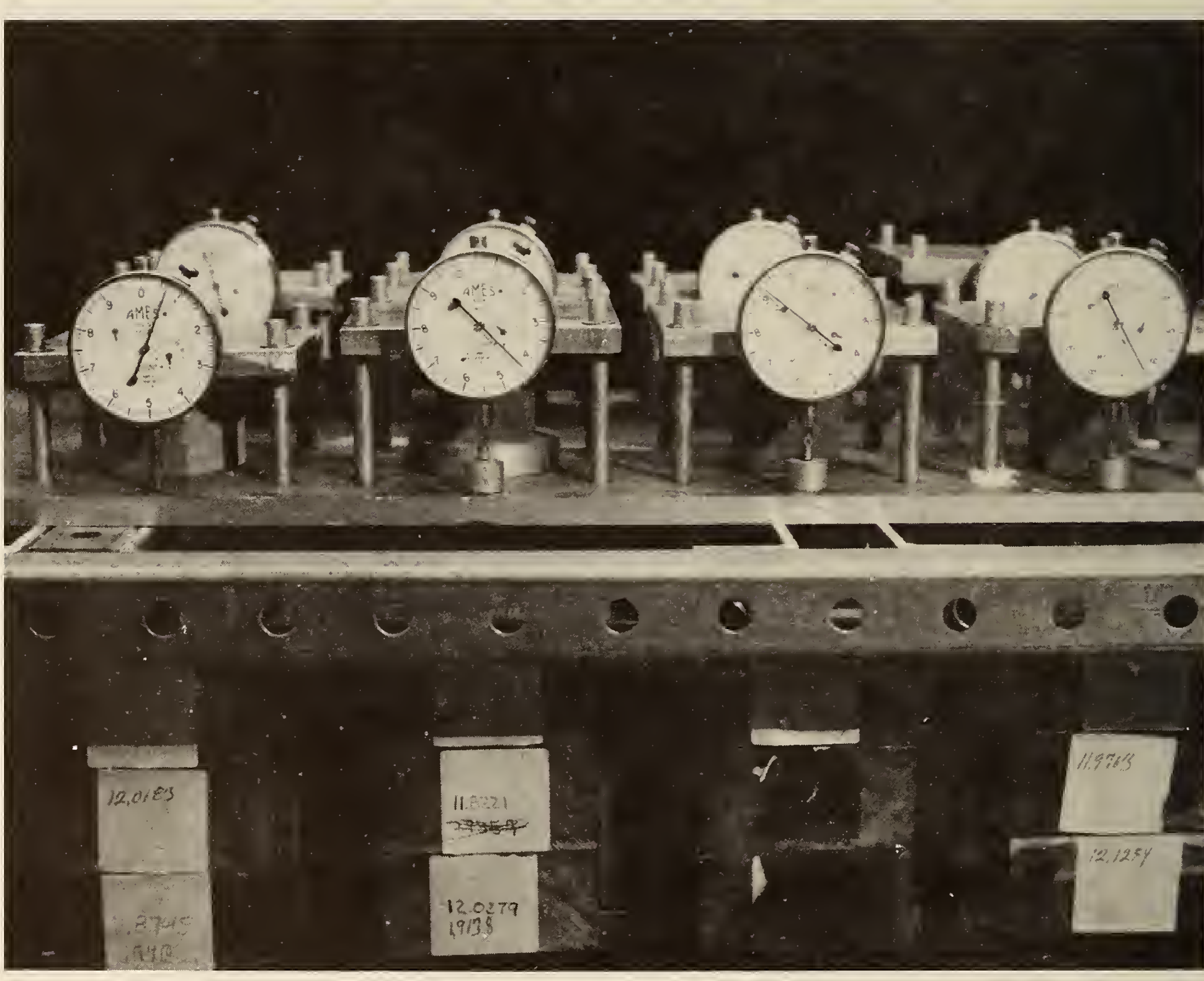

Figure 12. Creep of same adobe specimens selected from table 6. Applied load was 21 psi (0.14 MN/m^2)

6. PENETRATION TESTING OF ADOBE

A Method was developed by Winkler [20] for measuring the penetration resistance of adobe. He attached a needle to the head of a Soiltest Soil Penetrometer[1/] and measured the relative force required to insert the needle to a prescribed depth in adobe. This device was modified in the present study, and was used to develop relationships between the penetration resistance and moisture content and compressive strength of adobe.

6.1 TEST METHOD

Penetration resistance of the specimens used to construct the curves in Figure 2 were obtained immediately before their compressive strengths were measured. A modified penetrometer is shown in Figure 13. The portion which penetrated the adobe was machined down from the original 0.25 inch (6.3 mm) diameter rod to a cone with a base diameter of 0.063 (1.6 mm) and a height of 0.063 inch (1.6 mm). During testing, only the force required to completely embed the cone in the adobe was applied. Penetration values were taken from the sliding scale on the barrel of the penetrometer. Ten measurements were taken on each specimen, and the average values were used in constructing the curves shown in Figures 14 and 15.

6.2 RESULTS AND DISCUSSION

Relationships between penetration resistance and moisture content of the three adobe systems are given in Figure 14. The linear regression equations were derived by combining the three sets of data. The regression coefficient for the equation relating moisture content to penetration is 0.87 and the standard error is 3%, i.e. M $\pm$ 3%. Similar curves for penetration resistance versus compressive strengths are given in Figure 15. In this case, the regression coefficient is 0.98 and the standard error is 21 psi (0.14 MN/m^2). These statistical analyses indicate that the modified penetrometer used in the NBS laboratory can give reliable predictions of moisture contents and compressive strengths of adobes. However, new calibration curves should be obtained when testing adobes which may have physical and chemical properties grossly different from the three systems tested in the present study. Furthermore, measuring the penetration resistance of the surface layers of an adobe may not give results characteristing of the interior of the adobe.

1/ This instrument is identified in this paper in order to adequately specify the experimental conditions. This identification does not imply recommendation or endorsement by the National Bureau of Standards.

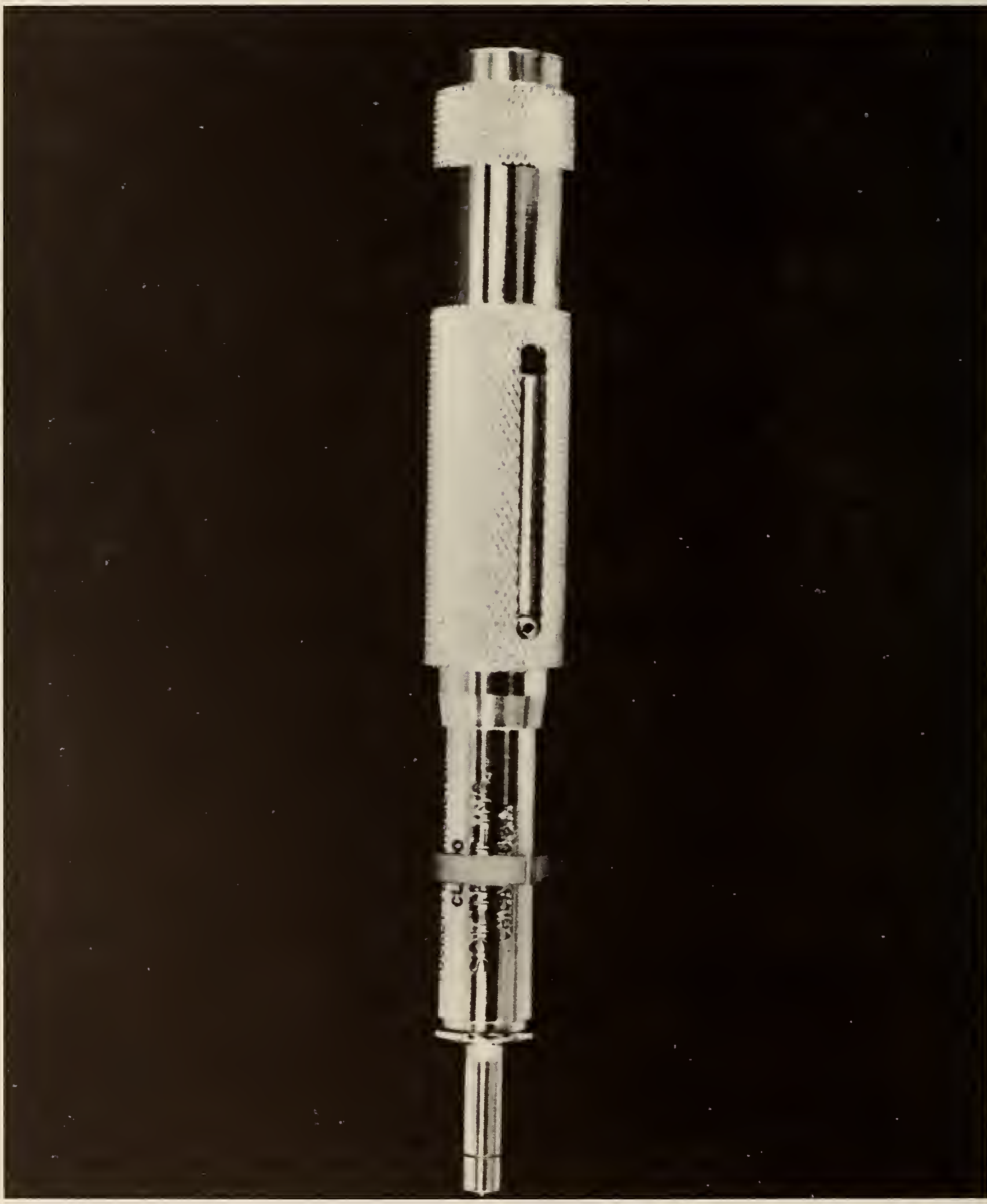

Figure 13. Penetrometer used to measure penetration resistance of adobe

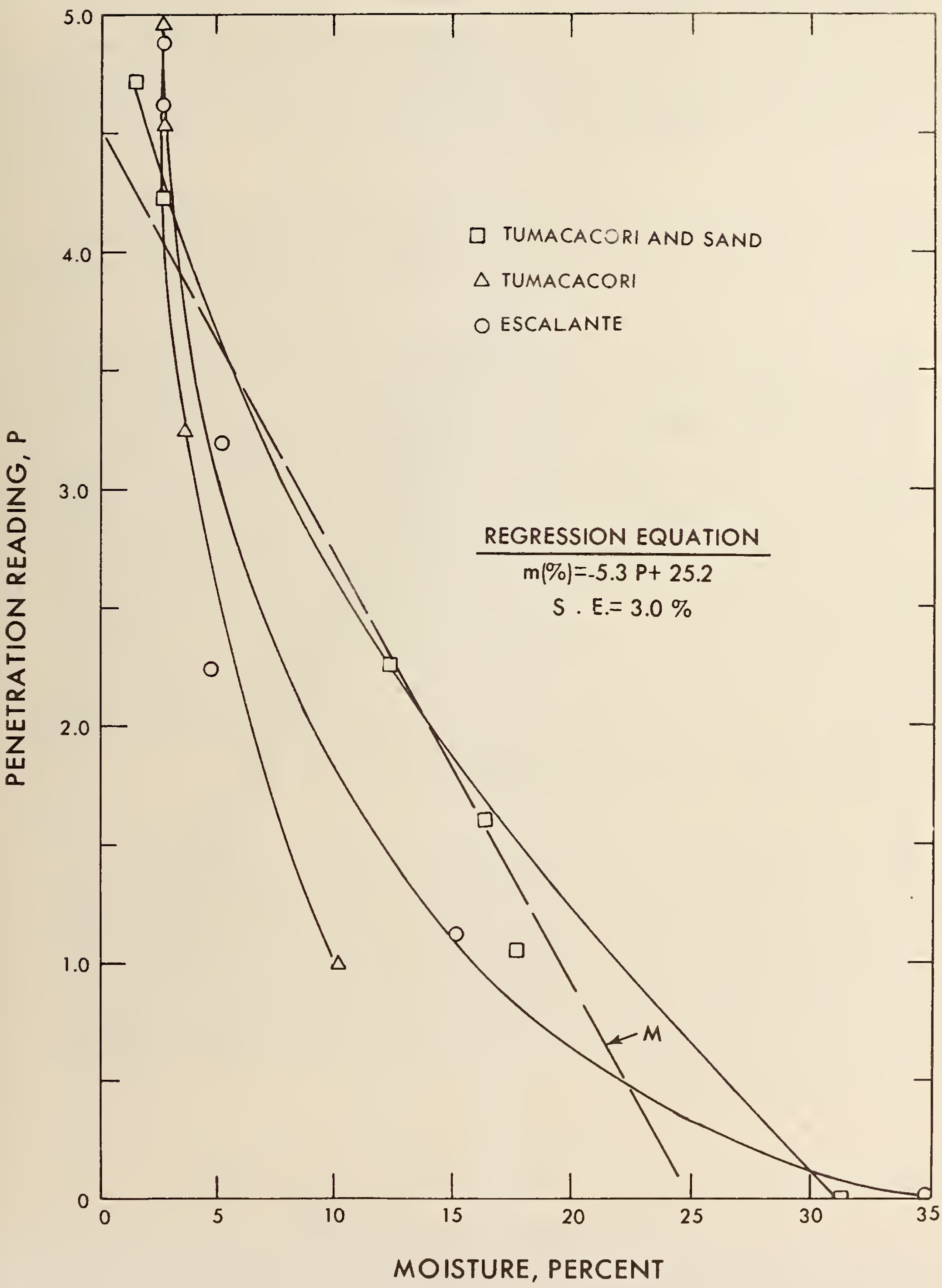

Figure 14. Relationship between penetration resistance and moisture contents (M) of adobe.

7. SUMMARY AND CONCLUSIONS

In this study, the effects of mix proportions, curing conditions, relative humidity, water contents, and wet-dry cycles on the compressive strength of adobe were investigated. The flexural strength of one adobe was also measured. In addition, the creep of dry and wet adobe was characterized.

A non-destructive test method, based on measuring the penetration resistance, was found to give reliable prediction of the compressive strength and moisture content of adobe. However, for different types of adobe, new calibration curves should be developed.

Of the experimental factors studied, moisture and wet-dry cycles were found to have the most deleterious effect on the compressive strength of adobe. Moisture also had a significant effect on the creep of adobe. For example, creep of wet adobe specimens were 200% greater than the creep of dry specimens. Adobe can become wet by absorption of rain, absorption of ground water and by absorption of moisture during periods of high relative humidities. The effects of these processes and also wet and dry cycles on the mechanical properties of adobe will depend on the severity of the conditions. Because of the low relative humidities normally present in the arid southwestern states, ground water and rain water are probably the main source for excess moisture in historic adobe structures located in such areas. Therefore, it appears that providing an abode structure with a water-tight roof and positive ground drainage will greatly assist in mitigating the most severe processes by which water reduces the mechanical properties of adobe.

An obvious need exists for the development and establishment of standard test methods to characterize the important mechanical properties of adobe. For example it has been found in this study that the drying conditions and moisture contents affect the compressive strength of adobe specimens. Other important factors, which no doubt affect compressive strength, include method of preparing specimens, shrinkage of specimens, and the loading rate. Unless these and other factors are controlled or measured it will remain difficult to compare the data from different laboratories, or even from the same laboratory.

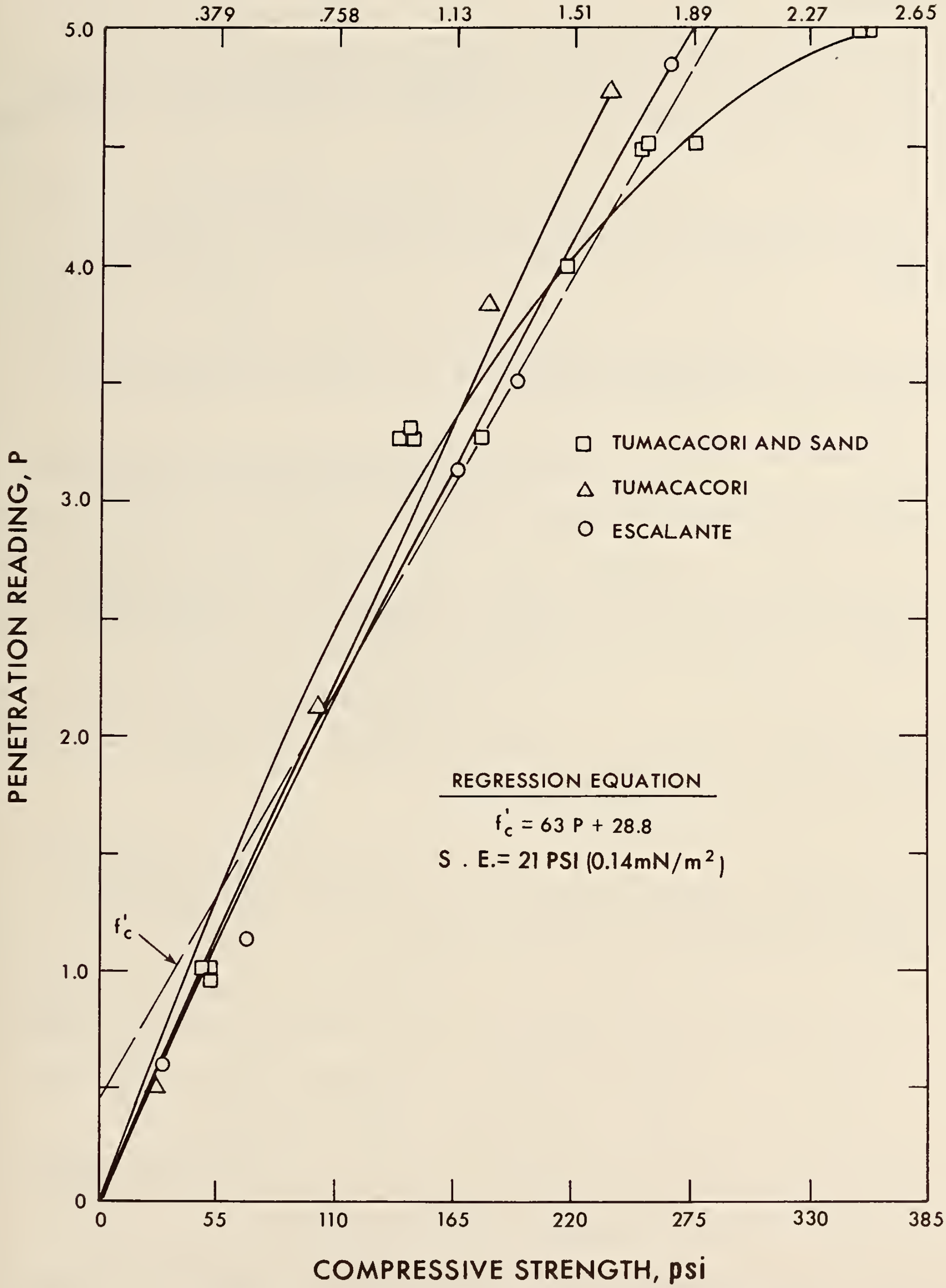

Figure 15. Relationship between penetration resistance and compressive strength (f_c') of adobe

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NBS-114A (REV. 11-77)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBS TN 996	2. Gov't Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE

Mechanical Properties of Adobe

5. Publication Date: May 1979

6. Performing Organization Code

7. AUTHOR(S) James R. Clifton and Frankie L. Davis

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)*

U. S. Department of the Interior
National Park Service
Washington, D. C. 20240

13. Type of Report & Period Covered

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Relationships between the compressive strength and creep, and the moisture contents of adobe were investigated. Moisture was found to have a deleterious effect on these mechanical properties of adobe, its severity increasing with increasingly higher relative humidities and higher moisture contents. It was concluded that rain and ground water would have a greater deleterious effect on the mechanical properties of adobe than high relative humidities.

The physicochemical properties of adobe, mix proportions, drying conditions, and shrinkage of specimens were also found to influence the compressive strength of adobe. Procedures for preparing, curing and testing of adobe specimens are given.

A nondestructive test method, based on measuring the penetration resistance of adobe, was found to give reliable predictions of the compressive strength and moisture content of adobe specimens.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Adobe; adobe soil; compressive strength; creep; flexural strength; mechanical properties; moisture; non-destructive testing; preservation.

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[ ] Order From National Technical Information Service (NTIS) Springfield, Virginia 22151

19. SECURITY CLASS (THIS REPORT)	21. NO. OF PAGES
UNCLASSIFIED	45
20. SECURITY CLASS (THIS PAGE)	**22. Price**
UNCLASSIFIED	$2.25

USCOMM-DC 66035-P78

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